PHYSICS @ INO

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NuFact 2013, August 19-24, Beijing, China
The Unknowns...after $\theta_{13}$

- The neutrino mass ordering ($MH$)...
- $CP$ violation in the lepton sector...
- Octant of the mixing angle $\theta_{23}$ ...
- Beyond 3-flavor oscillation physics..
The Unknowns...after $\theta_{13}$

We will cover in this talk:

- The neutrino mass ordering (MH)...
- CP violation in the lepton sector...
- Octant of the mixing angle $\theta_{23}$ ...
- Beyond 3-flavor oscillation physics using atmospheric neutrinos

3 posters and a talk on details of INO by Kaur, Laksmi, Meghna

Plenary talk by Naba Mondal on Friday
Matter Effects in Neutrinos

- Large fluctuations in $\Delta P$ in both $E$ as well as $\Theta$
- Need good reconstruction in both $E$ as well as $\Theta$ - resolution
- $\Delta P$ opposite for neutrino and antineutrino - charge id

Figure 1: The difference in the muon neutrino survival probability for normal and inverted hierarchy, $\Delta P_{\mu\mu}$, for various neutrino energies and zenith angles. The left panel shows $\Delta P_{\mu\mu}$ as a function of the neutrino energy for four different path lengths in the earth matter. The right panel shows $\Delta P_{\mu\mu}$ as a function of the neutrino zenith angle for four different choices of the neutrino energy.

Table 1: Benchmark true values of oscillation parameters used in the simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>True value used in data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2_{21}$</td>
<td>$7.5 \times 10^{-5} eV^2$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.3</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.5</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>0.1</td>
</tr>
<tr>
<td>$\delta_{CP}$</td>
<td>0</td>
</tr>
</tbody>
</table>

Ghosh, SC, arxiv:1306.1423
Matter Effects in Muons

- Smearing due to the $\nu$-nucleon cross-section
- Smearing due to presence of both $\nu_\mu$ and $\nu_e$ in the atm flux
- Smearing due to finite detector resolution
Residual matter effects still present which gives MH
Net sensitivity depends on the detector performance

Two key ingredients:
- Smearing due to resolution and efficiency
- Smearing due to presence of both $\nu_\mu$ and $\nu_e$ in the atm flux
- Smearing due to finite detector resolution
energy resolution and reconstruction from the muon analysis alone seems to be extremely plausible adjusting the exposure of the experiment. On the other hand, analysis of the muon data alone. We reiterate the the reconstruction contours for

\[ E_{\mu} \]

obtained in [28] using the full detector simulation results. In the combined statistical analysis.

Finally, in the left panel of Fig. 6, we show contours of constant \( \chi^2 \) as a function of the reconstruction and energy resolution plane. The left panel on Fig. 5 we show the contours from the analysis which uses only the muon data from the experiments. The right panels shows the constants for the analysis in which both muons and hadrons are included in our analysis. For \( \sigma_{E/E} < 4\% \) and \( \epsilon > 95\% \)

\[ \chi^2 > 14 \] (muons)

\[ \chi^2 > 9 \] (muons)

For \( \sigma_{E/E} < 5\% \) and \( \epsilon > 90\% \)

\[ \chi^2 > 12 \] (muons)

\[ \chi^2 > 8 \] (muons)

INO \( \mu \) angle resoln is good. We take \( \sigma_{\cos \Theta} = 0.025 \)

\[ \Delta \chi^2 = 6 \]

\[ \Delta \chi^2 = 7 \]

\[ \Delta \chi^2 = 8 \]

\[ \Delta \chi^2 = 9 \]

\[ \Delta \chi^2 = 10 \]

\[ \Delta \chi^2 = 11 \]

\[ \Delta \chi^2 = 12 \]

\[ \Delta \chi^2 = 13 \]

\[ \Delta \chi^2 = 14 \]

\[ \Delta \chi^2 = 15 \]

\[ \Delta \chi^2 = 16 \]

Ghosh, SC, arxiv:1306.1423

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NuFact 2013, August 21
Matter Effects in Neutrinos

Detector resolutions *extremely crucial*

Ghosh, SC, arxiv:1306.1423
**Matter Effects in Neutrinos**

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**Neutrinos**

- Oscillated $\nu_e$ events
- Oscillated $\nu_x$ events
- Smeared $\mu$ events

**Muons**

- Oscillated $\mu$ events
- Oscillated $\nu$ only disapp channel
- Smeared $\nu$ events

*Net matter effects in neutrinos and muons is the same after putting detector resolutions - even for very optimistic neutrino resolutions*

Ghosh, SC, arxiv:1306.1423

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Sandhya Choubey

NuFact 2013, August 21
Matter Effects in Neutrinos

\[ \Delta \chi^2 = 9 \text{ for } 21\% \text{ E-resoln} \]

which is the E-resoln for dets like INO/MIND- this is the same as you get from a *very* conservative muon analysis!!

\( \Delta \chi^2 = \frac{\sigma_{E_\mu}/E_\nu}{\text{Reconstruction efficiency } 80\% \text{ and charge id efficiency } 99\%} \)

\( \Delta \chi^2 \approx 12 - 13 \) (cf. Table 3).

If the muon energy resolution was improved to 2\%, then we would have a more than 4\(\sigma\) sensitivity to the mass hierarchy from the muon-plus-hadron analysis. Whereas, from Fig. 4 we can see that the sensitivity from the neutrino analysis cannot match the numbers, even for extremely optimistic energy resolution of 10\%.

The reason can be traced to even more plots shown in Figs. 2, 3 and 4. The effects of the detector resolutions on the neutrino spectra make it comparable, and sometimes even worse than the muon spectrum. If we add the hadron spectral data to the muon spectral analysis, we get an additional contribution to the hierarchy sensitivity which cannot be matched by the neutrino analysis.

For comparison, in Fig. 7 we also show the \( \Delta \chi^2 \) obtained when we bin the data in neutrino energy and muon zenith angle bins. We keep the reconstruction efficiency at 80\% and charge identification efficiency at 99\%. The muon zenith angle resolution function is taken with width 0.01. We see that the \( \Delta \chi^2 \) obtained in this case is even worse than what we had obtained with the neutrino zenith angle analysis using \( \Theta\)-resoln from Monolith.
Matter Effects in Neutrinos

Using the hadron data to reconstruct the neutrino is not helping much... using $\Theta$-resoln from Monolith.

$\Delta \chi^2 = 9$ for 21% E-resoln which is the E-resoln for dets like INO/MIND- this is the *very* conservative muon analysis!!

$\Delta \chi^2 = 9$ for 21% E-resoln which is the E-resoln for dets like INO/MIND- this is the *very* conservative muon analysis!!

Ghosh, SC, arxiv:1306.1423
Matter Effects in Hadrons

Hadrons are tagged with the muon direction.

Matter effects in hadrons present... will give MH sensitivity.

Though significantly less than in muons.

Detector resolution less important for hadrons.

Ghosh, SC, arxiv:1306.1423
MH@INO (Muon+Hadron)

Hadrons are tagged with the muon direction.

For $\sigma_{E/E}<4\%$ and $\varepsilon>95\%$

$\Delta \chi^2>20$ (muons+hadrons)

$\Delta \chi^2>14$ (muons)

For $\sigma_{E/E}<5\%$ and $\varepsilon>90\%$

$\Delta \chi^2>18$ (muons+hadrons)

$\Delta \chi^2>12$ (muons)

For $\sigma_{E/E}<6\%$ and $\varepsilon>85\%$

$\Delta \chi^2>16$ (muons+hadrons)

$\Delta \chi^2>10$ (muons)
Hadrons are tagged with the muon direction. For $\sigma/E<4\%$ and $\varepsilon>95\%$
$\Delta\chi^2>20$ (muons+hadrons)

For $\sigma/E<5\%$ and $\varepsilon>90\%$
$\Delta\chi^2>18$ (muons+hadrons)

For $\sigma/E<6\%$ and $\varepsilon>85\%$
$\Delta\chi^2>12$ (muons+hadrons)

For $\sigma/E<10$ (muons+)
$\Delta\chi^2>10$ (muons+hadrons)

$\Delta\chi^2>16$ (muons+hadrons)

One can get $\Delta\chi^2=9$ with 5 years INO data

$\Delta\chi^2=14$ (muons+hadrons)

Reconstruction efficiency

Ghosh, SC, arxiv:1306.1424

MH@INO (Muon+Hadron)
MH - $\mu+h$ vs $\nu$ Analysis

Muon+Hadron analysis gives $\Delta \chi^2 = 16$ for $\sigma_E(\mu) = 6\% E$ and $\sigma_\Theta(\mu) = 0.025$ in $\cos \Theta$ .... both are realistic for INO/MIND

To get the same $\Delta \chi^2 = 16$ using the neutrino analysis, one needs $\sigma_E(\nu) = 10\% E$ and $\sigma_\Theta(\nu) = 7.3^\circ$....the energy resol requirement not possible at INO/MIND

Better to use the hadron data separately in the $\chi^2$ than using it to reconstruct the neutrino energy and angle
Octant @ INO

For $\sin^2 \theta_{23} < 0.4$
$\Delta \chi^2 > 2.44$ (INO)
$\Delta \chi^2 > 9$ (LBL+React)
$\Delta \chi^2 > 12.3$ (INO+LBL+React)

Sensitivity for IH is worse
Conclusions

- With 5% $E_\mu$-resoln and 90% efficiency, INO will have $\Delta \chi^2 = 12$ in 10 years from muon data alone.

- If we tag the hadrons with the muons and add the hadron data separately into a combined analysis, then with 5% $E_\mu$-resoln and 90% reconstruction efficiency INO could have $\Delta \chi^2 = 9$ in just 5 years.

- Using the hadrons to reconstruct the neutrino energy and directions will always yield poorer results.